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MONSOONS AND THE GLOBAL CIRCULATION

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Summary. This paper considers the role of monsoons within the global circulation of the atmosphere. Previous work on this subject is reviewed briefly and the role of the monsoon is discussed in terms of the essentially convective nature of the troposphere.

Introduction. It is inevitable that extensive reorganizations of the tropical cell of the general circulation of the atmosphere will have widespread repercussions elsewhere, for the principle of continuity is fundamental in meteorology. It would be surprising if these repercussions were confined to the tropical zone, because extratropical circulations are known to extend well into tropical latitudes.[1,2,3] Accordingly, it is to be expected that repercussions of monsoons will be evident in middle latitudes.

Early attempts to establish relationships between monsoons and atmospheric behaviour elsewhere, reviewed critically by Normand,[4] employed statistical analyses, with only scant regard for physical justification. Some intricate statistical associations between Indian monsoon phenomena and diverse atmospheric factors far away were derived (e.g. Ramdas *et alii*[5]) but the paucity of upper-air information precluded a satisfactory physical understanding of the associations. Consequently, the associations were unreliable as tools for the forecasting of Indian monsoon behaviour, for which primarily they were intended.

Normand mentioned that Sir Gilbert Walker, about 50 years ago, attempted, albeit inconclusively, to explain in *physical* terms a statistical relationship he discovered between South American pressure in April and May and Indian monsoon rainfall between June and September. Walker's work led to the discovery of the phenomenon which he called 'the southern oscillation'. Normand described this phenomenon briefly as 'a tendency for air to be removed from the whole Pacific area from Tokyo to South America at the same time as air accumulates in and around the Indian Ocean and vice versa'. The phenomenon is evident not only in values of surface pressure but also in temperature and rainfall records of India, Indonesia and Australia. Walker showed by correlation techniques that the Indian monsoon rains are related to later, rather than earlier, atmospheric events over the globe.

Troup[6] discussed at length and updated Walker's work and suggested a mechanism for the oscillation in terms of a direct toroidal circulation between the warmer eastern and the cooler western hemispheres. Wright[7] mentioned that certain aspects of the southern oscillation may be influenced by a biennial cycle in tropospheric circulations and suggested that this cycle is tidal in origin.

Aerological relationships. One of the earliest comprehensive aerological investigations of the onset of the Indian monsoon was carried out by Yin.[8] He reviewed briefly earlier aerological studies and then showed from his own analyses that the onset in 1946 was associated with a disappearance of the upper-tropospheric westerly flow over northern India and with a rearrangement of the pattern of long waves over the northern hemisphere. Frost[9] established that the height of the tropopause over the Middle East alters abruptly from near 220 mb to near 80 mb at the end of May and vice versa in October, and Sutcliffe and Bannon[10] showed additionally that a simultaneous reversal of direction of the upper-tropospheric flow over the Middle East correlates well with the date of onset of the monsoon rains on the Indian Malabar coast. Likewise, Ananthakrishnan and Rangarajan[11] found that the tropopause characteristics over the northern part of the Indian subcontinent alter markedly from extratropical to tropical, and vice versa, with the onset and retreat respectively of the Indian south-west monsoon.

Yeh *et alii*[12] claimed that the abrupt change of the upper-tropospheric circulation is not a special condition, found only in Asia, but a world-wide phenomenon. They proposed that there are only two natural atmospheric seasons, winter and summer, of which winter is the longer. Spring and autumn, they said, are merely short transition periods between the natural seasons. They mentioned also that a good correlation exists between the beginning of the 'Mai-yü' period over eastern Asia and the establishment of the Indian monsoon. Moreover, they suggested that the 'Indian summer' in North America and the 'old wives' summer' in Europe may be related to the October upper-tropospheric transition period. Dao and Chu[13] showed that there is a correspondence between movements of the surface anticyclone over the north-western Pacific Ocean and variations of the upper-tropospheric anticyclone over Tibet (see also Neyama,[14] and Gordon[15]). Chang[16] has reviewed the many studies made of relationships, known or suspected, between circulations over eastern Asia and the Indian monsoons.

De la Mothe and Wright[17] pointed out that, despite the sufficiency of upper-air data in the extratropics, not much attention had been paid to relationships which were known to exist between the onset of the Indian south-west monsoon and changes in the circumpolar westerlies of middle and high latitudes. Accordingly, they examined 500-mb trough–ridge patterns over Europe and Asia in search of a relationship with the onset of the Indian summer monsoon. They concluded that the 500-mb flow in the circumpolar westerlies over Eurasia plays a significant role in the mechanism of the onset of this monsoon and they advised that 'close attention' should be given to the Asian ridge, and changes of wavelength of the long-wave pattern across it, at the time of monsoon onset (see also Gordon[18]).

The work of Anjaneyulu and Sikka[19] supported Sir Gilbert Walker's conclusion that circulation changes in higher latitudes are determined largely

by monsoons. Pisharoty[20] too was of the opinion that the Indian monsoon is a source of energy which exerts a significant influence on the general circulation of the atmosphere. Indeed, it is surely unrealistic to attempt to show that circulation changes in middle latitudes are *responsible* for the Indian summer monsoon since the sun is the principal energy source for the global circulation. However, it is expected that extratropical circulations provide feedback within the atmospheric system to the tropics, thereby exerting a regulating influence.

Monsoons and extratropical circulations. The schematic vertical section of flow in deep tropospheric convection shown in Figure 1 is due to Green *et alii*.[1] According to these authors :

> 'The pattern of vertical motion is markedly asymmetrical, the upward velocities being large and concentrated into a small part of the system where the condensation of water vapour occurs. In and near this region the flow is rapid and may be nearly adiabatic, and a large part of the condensed water is precipitated. Outside it, descending motion is cloud free and, for return to the surface layer in the same latitude, is limited to the slow rate determined by radiative heat loss.'

They estimated that air may take three weeks or more to return from the upper to the lower troposphere. Further, they suggested that subsiding air is moistened in regions of small-scale convection, illustrated in Figure 1, and thereby provided with potential energy. This moistened air then enters middle-latitude trough–ridge circulations (termed by Green *et alii*[1] 'large-scale slope-convection systems') and ascends on the eastern flanks of troughs, and the potential energy is converted into the kinetic energy of jet streams. Published examinations of these proposals are scarce, but Walker[21,22] showed that their ideas could be applied to winter jet streams near 300 mb and to the associated cloud and precipitation events over the coasts of Iran and West Pakistan, at the foothills of the Himalayas and over the plains of central Asia.

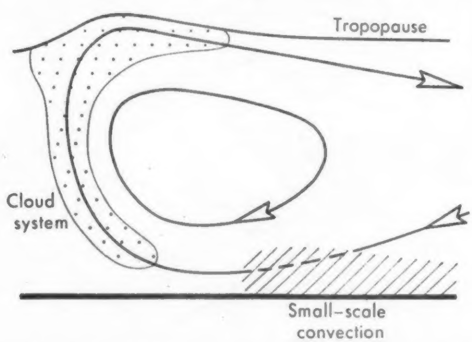

FIGURE 1—SCHEMATIC VERTICAL SECTION OF FLOW IN DEEP TROPOSPHERIC CONVECTION (after Green *et alii*[1])

Ramage[23] concluded that air which subsides widely over south-west Asia in summer ascends originally over a relatively small area in Indian monsoon rain systems. The present author's analyses, based upon both climatic and daily surface and aerological observations and employing, in particular,

winds and wet-bulb potential temperatures, support Ramage's conclusion and indicate that air which ascends in monsoon rain systems over Ethiopia and over western North Africa subsides subsequently over the central Sahara Desert and the eastern North Atlantic Ocean respectively. The lack of data over large tracts is, of course, a hindrance in such studies. Suggested trajectories are shown in Figures 2 and 3.

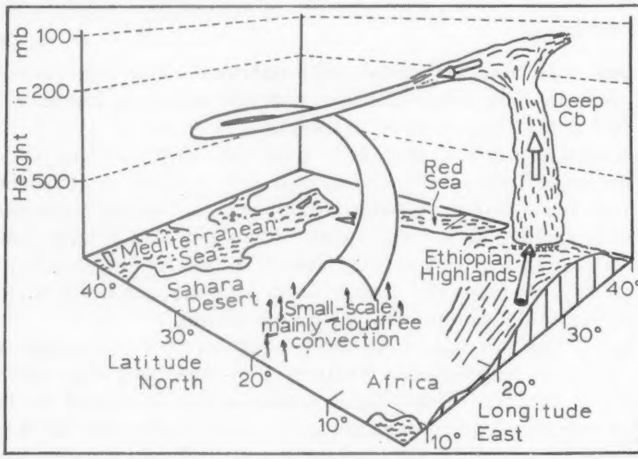

FIGURE 2—MODEL OF FLOW IN THE MONSOON CIRCULATION OF EASTERN NORTH AFRICA

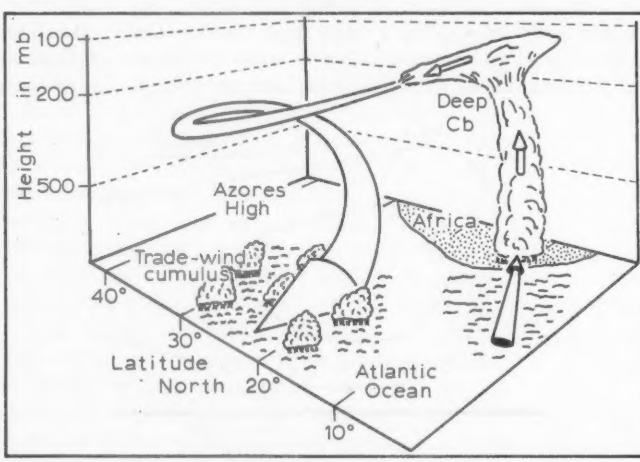

FIGURE 3—MODEL OF FLOW IN THE MONSOON CIRCULATION OF WESTERN NORTH AFRICA

Hence, a plausible explanation is provided for the well-known summer intensification and extension eastward of the subtropical anticyclone over the North Atlantic Ocean (the so-called 'Azores high'). In summer this anticyclone contains, in addition to air subsiding from the intertropical

convergence zone over the Atlantic Ocean in a conventional Hadley-type circulation, air subsiding from the monsoon rain systems over western North Africa. This suggests that the intensity of the Azores high is controlled to some extent by the monsoonal activity; there is some observational evidence, on both synoptic and seasonal time-scales, that this is indeed so, but the idea needs a thorough investigation.

Carlson and Ludlam[24] and Green *et alii*[1] mentioned that subsiding air may be prepared in regions of small-scale convection over the Sahara Desert for ascent on the eastern flanks of summer troughs over Europe. Spectacular evidence for the participation of Saharan air in such troughs was provided by the dust fall of 1 July 1968 over southern Britain (Stevenson[25]); scientific analyses of this dust indicated that its origin was near the southern edge of the Sahara Desert, near the Ahaggar Mountains. Stevenson remarked that broad southerly airstreams from North Africa ordinarily occur several times a year and it is perhaps surprising that noticeable falls of dust are not more frequent.

Cyclogenesis is favoured beneath divergent regions in the upper troposphere. The assumption that the upper-tropospheric easterly flow in the tropics in summer decelerates *gradually* downwind from India is not supported by observations. It is true that the average strength of this flow is greatest over India but it happens often that upper-tropospheric winds are stronger over eastern North Africa than over India. Moreover, both climatically and on individual days, separate wind-speed maxima can be identified downwind of India, one above the Ethiopian Highlands and another above western North Africa (Figures 4 and 5). Accordingly, although there is, as Flohn[26] has shown, a general tendency for subsidence to occur in the middle and upper troposphere between the western Sahara and Pakistan, the precise distribution of convergences and divergences from day to day is complex.

The suggestion implicit in the present author's analyses is that subsiding air from Ethiopian monsoon rain systems arrives in the lower troposphere over the central Sahara Desert. Preparation for ascent takes place there in

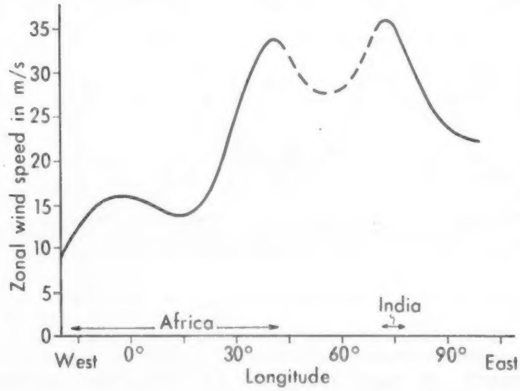

FIGURE 4—MONTHLY MEAN ZONAL WIND SPEEDS AT 150 mb IN JULY BETWEEN WESTERN NORTH AFRICA AND SOUTH-EAST ASIA

The cross-section is approximately along latitude 12°N.

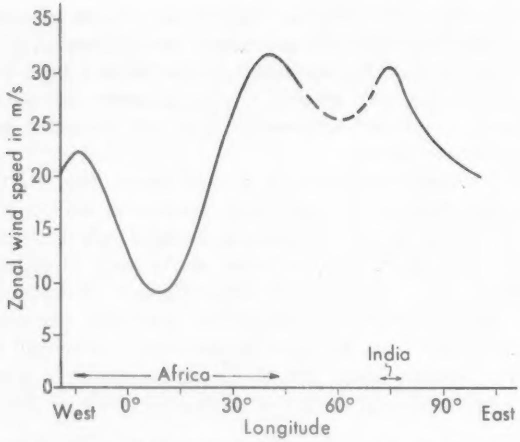

FIGURE 5—ZONAL WIND SPEEDS AT 150 mb AT 00 GMT ON 28 JULY 1966 BETWEEN WESTERN NORTH AFRICA AND SOUTH-EAST ASIA

The cross-section is approximately along latitude 12°N.

small-scale, generally cloud free, convection, in association with divergence aloft, the divergence being associated with fluctuations in the strength of the upper easterly flow over North Africa. Support for such a mechanism is provided by satellite photographs, which often reveal frontal cloud-bands extending from the Sahara well into western Europe (see Flohn[3]), and the origin, near the Ahaggar Mountains, of the aforementioned dust is also consistent with this mechanism.

Conclusion. Figure 6 summarizes the main features of the suggested collaboration of small-scale, monsoon-scale and large-scale slope convection over North Africa. Such collaboration between the various scales of convection

FIGURE 6—SUMMARY OF MAIN FEATURES OF SUGGESTED COLLABORATION OF THE VARIOUS SCALES OF CONVECTION OVER NORTH AFRICA

In the small-scale convection (C) over the central Sahara Desert the subsided outflow from the Ethiopian monsoon is prepared for ascent (A) in European trough–ridge systems. The outflow from the monsoon over western North Africa subsides over the Atlantic Ocean.

is an essential feature of the global tropospheric circulation (Ludlam[27]) and must form the basis of any investigation into the role of monsoonal reorganizations of the troposphere within that circulation.

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HYDROLOGY OF THE NORTH SEA: RUN-OFF AND PRECIPITATION

By J. GRINDLEY

Summary. Values of total accession of fresh water to the North Sea have been presented for the months January 1941 to December 1960. The data are shown separately for run-off from the rivers draining to the North Sea, for precipitation over the Sea and as a combined total. A graphical technique, relating specific discharge to average areal rainfall, was used to estimate run-off for areas for which no flow data were available. Precipitation was estimated by taking the mean of values from a number of stations ringing the Sea.

Introduction. The purpose of this synopsis is to provide information concerning total accession of fresh water to the North Sea in the form of run-off from the land areas of Europe draining to the Sea and precipitation over the Sea.

The data are provided for each month in the period January 1941 to December 1960. It is hoped that this period is sufficiently long to permit an adequate representation of the range and seasonal variation in the accession of fresh water.

The data are provided in three parts: total run-off; total precipitation; and total accession of fresh water, run-off and precipitation combined.

Total run-off to the North Sea. Table I shows total monthly run-off in cubic metres $\times 10^9$ contributed by all rivers draining to the North Sea in the period 1941–60. The data were obtained in the following way.

Eastern Britain. River flow data were obtained from the *Surface Water Year Books* prepared at that time by the Ministry of Housing and Local Government and the Scottish Office. The total area of eastern Britain for which river flow measurements were available was 24 834 km^2 in 1941 and 54 804 km^2 in 1960; the total area of eastern Britain draining to the North Sea is 115 472 km^2. That is, even in 1960, river flow measurements were available for less than half the area of Britain draining to the North Sea.

It was necessary, therefore, to estimate run-off for the portion of the country for which flow data were not available. The estimates were made by plotting, for each year, specific discharge (discharge per unit area) against average annual rainfall for all areas where river flow data were available. In most years, a close relationship was apparent and a smooth curve could be drawn. River flow from the non-gauged areas was computed for each hydrometric area (major river-division) by entering the graph for a particular year with estimated general rainfall over the non-gauged area and reading off a specific discharge. Total discharge from the non-gauged area was then obtained by multiplying specific discharge by area; to this was added the measured discharge to obtain a value of river flow for the whole hydrometric area.

The apportionment of annual amounts to individual months within the year was less satisfactory. River flow in the largest catchment in each hydrometric area and any other catchment of area greater than 130 km^2 was expressed as a percentage of the annual river flow for each year and the percentage values for each month were meaned to give a general percentage estimate for the whole of eastern Britain. The mean percentage value for each month was

TABLE I—TOTAL MONTHLY RUN-OFF TO THE NORTH SEA IN THE PERIOD 1941–60

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						cubic metres × 10^9							
1941	27	30	34	27	25	34	24	22	17	19	23	28	310
42	19	14	28	24	23	30	26	21	23	27	21	22	278
43	25	26	20	23	27	36	31	20	19	23	14	15	279
44	25	22	17	21	25	33	32	25	18	22	30	38	308
45	18	42	29	24	29	35	27	18	16	18	13	18	287
46	20	39	29	23	24	31	33	21	24	13	19	19	295
47	17	9	35	30	30	27	18	8	15	20	15	15	239
48	45	34	21	23	24	27	29	20	27	27	20	21	318
49	23	19	19	21	30	35	27	20	16	24	14	18	266
50	17	27	22	17	29	36	28	21	24	28	20	25	294
51	29	21	24	24	26	27	27	25	22	13	22	30	290
52	32	21	26	31	30	23	29	21	19	17	28	35	312
53	22	25	24	17	27	34	27	21	18	22	22	20	279
54	16	13	16	16	26	30	26	24	27	35	27	37	293
55	36	27	21	21	23	31	38	20	18	21	15	22	293
56	28	16	25	18	27	36	35	27	21	33	20	29	315
57	28	33	29	20	22	31	32	23	26	28	22	24	318
58	27	32	29	20	30	35	38	26	18	28	21	23	327
59	32	16	20	20	26	24	20	17	10	11	17	15	228
60	20	19	18	14	24	25	18	20	20	27	29	34	268
Mean 1941–60	25	24	24	22	26	31	28	21	20	23	21	25	290

then applied to the annual value for eastern Britain (obtained by summation of measured flow and flow calculated graphically) to give an estimate of discharge in each month for the whole of eastern Britain.

Western Denmark. Flow data for the whole of that part of Denmark draining to the North Sea (10 850 km²) were provided by Det Danske Hedeselskabs Kulturtekniske Afdeling, Hydrometriske Undersøgelser.

Netherlands. Flow data for the Rhine at Lobith (160 000 km²) and the Meuse (Maas) at Lith (29 500 km²) were provided by the Dutch Rijkswaterstaat, Directie Waterhuishouding en Waterbeweging.

Germany. Flow data for the Ems to its mouth (12 480 km²), Weser to its mouth (45 253 km²) and Elbe to its mouth (144 055 km²) were provided by the Bundesanstalt für Gewässerkunde.

Norway. Flow data for the area of Norway between Lindesnes and 62°N, draining to the North Sea were provided by Norges Vassdrags- og Elektrisitetsvesen, Vassdragsdirektoratet, Hydrologisk Avdeling.

Residual waters draining to the North Sea. Although measurements or estimates of flow were made available for the greater part of Europe draining to the North Sea, a number of residual areas remained for which neither estimates nor measurements were available. The largest of these areas was the Scheldt (21 000 km²). Professor Tison, then General Secretary of the International Association of Scientific Hydrology, was able to provide a limited amount of flow data for the Scheldt and its tributary the Rupel at their confluence. It was clear that, because of abstractions, diversions and feeding of canals, the measured flow in these rivers in no way represented the natural contribution of their catchment areas to run-off to the North Sea. It was necessary, therefore, to estimate flow for the Scheldt and for the remaining residual areas, namely the Rhine below Lobith (5500 km²), the Meuse below Lith (3370 km²), the coastal streams of Flanders (3231 km²) and the Ijsel (3600 km²).

The estimation was carried out by using a method similar to that adopted for estimating river flow in the non-gauged areas of eastern Britain. That is, average annual rainfall was estimated over the areas for which flow data (measured or estimated) were available and also over the residual areas. The mean specific discharge (cubic metres per second per square kilometre) for the years 1941–60 was obtained for each of the areas for which flow data were available and these specific discharges were graphed against average annual precipitation. Estimates of mean specific discharge were obtained for the residual areas by entering the graph with estimates of average annual precipitation over these areas. The average annual precipitation with apparent and estimated specific discharges are given in Table II.

TABLE II—AVERAGE ANNUAL PRECIPITATION AND ANNUAL SPECIFIC DISCHARGE FOR SPECIFIED AREAS

	Average precipitation *mm*	Annual specific discharge $m^3/s\ km^2$
Areas for which flow data were available		
Eastern Britain	861	0·0133
Western Denmark	760	0·0125
Rhine to Lobith	822	0·0131
Ems	712	0·0090
Weser	723	0·0085
Elbe	658	0·0055
Meuse to Lith	827	0·0101
Norway	1797	0·0769
		Estimates of annual specific discharge $m^3/s\ km^2$
Residual areas		
Rhine below Lobith	700	0·0060
Meuse below Lith	730	0·0080
Scheldt	815	0·0140
Flanders streams	750	0·0090
Ijsel	720	0·0080

Flow for individual months from the residual areas was then obtained by taking the ratio of specific discharge over each of these areas to that of a neighbouring area and increasing the observed flow in the neighbouring area for the particular month in that ratio. No great accuracy can be claimed for this method but it is considered that the estimated value will at least be of the right order.

Annual flow from each major area. Table III shows the annual flow, 1941–60, in cubic metres $\times 10^9$ from each of the major areas contributing discharge to the North Sea. The values for the residual areas represent the means of the 12 monthly values rather than the more correct means of daily values.

Monthly precipitation over the North Sea. Table IV shows monthly precipitation in millimetres and Table V the equivalent volume in cubic metres $\times 10^9$ over the North Sea. The area of the North Sea which has been adopted is that proposed by T. Laevastu* (Fisheries Oceanographer, Food and Agriculture Organization). It is bounded in the north by a line running approximately from Nord Fiord, Norway, to Shetland, Orkney, and the mainland of Scotland, and to the south by a line from Dover to Calais. The Skagerrak and Kattegat are excluded. The extent of this area is given as 575 300 km^2.

* LAEVASTU, T.; Synopsis of information on the oceanography of the North Sea. FAO, Fisheries Division, Biology Branch, 1960. (Unpublished, copy available in the Meteorological Office, Met.O.8a.)

TABLE III—ANNUAL FLOW FROM MAJOR AREAS OF EUROPE CONTRIBUTING WATER TO THE NORTH SEA

Year	Eastern Britain	Western Denmark	Rhine to Lobith	Ems	Weser	Elbe	Meuse to Lith	Norway	Rhine below Lobith	Meuse below Lith	Scheldt	Flanders	Ijsel
	115 472	10 850	160 000	12 480	45 253	144 055	29 500	45 474	5500	3370	21 000	3231	3600 km^2
						cubic metres × 10^9/year							
1941	54	3	87	5	17	47	11	70	1	1	11	1	1
42	43	4	60	3	12	26	8	111	1	1	8	1	1
43	43	4	46	3	8	15	8	144	1	1	8	1	1
44	42	4	74	4	13	27	11	117	1	1	11	1	1
45	45	5	69	4	12	24	9	109	1	1	9	1	1
46	51	5	66	4	14	26	9	109	1	1	9	1	1
47	50	3	50	2	9	18	6	92	1	1	6	1	1
48	49	4	77	4	13	26	11	120	1	1	11	1	1
49	38	4	38	2	7	17	5	147	1	1	5	1	1
50	48	5	58	3	11	19	9	129	1	1	9	1	1
51	62	6	70	4	11	17	12	93	1	1	12	1	1
52	52	5	80	3	12	20	14	108	1	1	14	1	1
53	40	5	54	2	9	20	7	130	1	1	7	1	1
54	63	6	61	4	10	19	8	109	1	1	8	1	1
55	44	5	72	3	14	31	8	104	1	1	8	1	1
56	46	4	75	5	18	33	10	109	1	1	10	1	1
57	50	4	65	4	14	28	11	127	1	1	11	1	1
58	59	5	80	5	17	21	13	98	1	1	13	1	1
59	40	4	50	1	7	18	7	92	1	1	7	1	1
60	63	4	68	3	9	21	10	75	1	1	10	1	1
Mean 1941–60	49	4	65	4	12	24	9	110	1	1	10	1	1

TABLE IV—MONTHLY PRECIPITATION OVER THE NORTH SEA (AREA 575 300 SQUARE KILOMETRES)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						millimetres							
1941	38	62	50	30	35	21	79	119	31	101	64	67	697
42	63	29	31	30	58	34	91	66	93	125	70	97	787
43	92	64	30	58	56	55	42	88	74	69	111	46	785
44	85	42	40	45	48	65	53	53	117	96	124	82	850
45	74	72	30	48	75	56	50	76	69	70	44	88	752
46	58	75	49	46	40	76	90	99	118	47	109	74	881
47	41	31	78	58	28	58	58	14	78	31	113	63	651
48	112	49	31	45	42	66	56	92	95	85	59	78	810
49	88	48	45	63	43	32	36	56	61	104	95	104	775
50	52	80	47	62	38	61	88	110	127	71	110	81	927
51	81	72	68	73	40	43	63	115	68	36	127	87	873
52	74	46	64	37	39	66	61	99	101	85	88	79	839
53	51	53	23	58	54	48	83	103	70	51	78	63	735
54	62	54	50	26	49	68	86	87	103	124	104	101	914
55	59	47	39	35	62	41	20	33	77	103	43	96	655
56	104	36	29	27	38	53	83	110	62	86	60	76	764
57	68	76	62	24	37	44	85	105	107	90	76	72	846
58	82	77	45	42	69	47	93	107	70	89	52	83	856
59	87	18	41	61	19	46	55	48	23	83	102	99	682
60	87	59	26	44	35	42	77	96	68	110	111	96	851
Mean 1941–60	73	54	44	46	45	51	67	84	81	83	87	82	797

TABLE V—MONTHLY PRECIPITATION OVER THE NORTH SEA (AREA 575 300 SQUARE KILOMETRES)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						cubic metres $\times 10^9$							
1941	22	36	29	17	20	12	45	68	18	58	37	39	401
42	36	17	18	17	34	19	52	38	53	72	40	56	452
43	53	37	17	33	32	32	24	51	43	39	64	26	451
44	49	24	23	26	28	37	30	31	67	55	72	47	489
45	43	42	17	28	43	32	29	44	40	40	25	50	433
46	33	43	28	26	23	43	52	57	68	27	63	43	506
47	24	18	45	33	16	33	33	8	45	18	65	36	374
48	64	28	18	26	24	38	32	53	55	49	34	45	466
49	51	27	26	36	25	18	21	32	35	60	55	60	446
50	30	46	27	35	22	35	51	63	73	41	63	47	533
51	47	41	39	42	23	25	36	66	39	21	73	50	502
52	42	26	37	21	23	38	35	57	58	49	51	46	483
53	29	31	13	33	31	28	48	59	40	29	45	36	422
54	36	31	29	15	28	39	50	50	59	71	60	58	526
55	34	27	22	20	36	23	12	19	45	59	25	55	377
56	60	21	17	16	22	30	47	63	36	49	34	44	439
57	39	44	35	14	21	25	49	61	62	52	44	41	487
58	47	44	26	24	40	27	53	62	41	51	30	48	493
59	50	10	24	35	11	27	32	27	13	48	59	57	393
60	50	34	15	25	20	24	45	56	39	63	64	55	490
Mean 1941–60	42	31	25	26	26	29	39	48	47	48	50	47	458

The estimates were made by taking 17 rainfall stations, more or less evenly spaced round the coasts of the North Sea and adopting a simple arithmetic mean of the monthly totals at these stations to obtain an estimate of areal general rainfall over the Sea. The assumption in this approach is that, in the absence of relief or other factors likely to induce precipitation, linear interpolation is possible. Although the stations were chosen to be as close

to sea level as possible, it seems likely that in all cases the land mass on which they stand will have had some effect on the precipitation at the station. Again, it is hoped that the estimates are of the right order, but it seems likely that they are even less certain than those for run-off. The uncertainty is almost certainly in the direction of overestimation.

The stations used were :

	Latitude	Longitude
United Kingdom		
Lerwick	60°08′N	1°11′W
Hellgar Holm	59°01′N	2°54′W
Kinnaird's Head	57°42′N	2°00′W
Carnoustie	56°30′N	2°42′W
Tynemouth	55°01′N	1°25′W
Hornsea	53°55′N	0°10′W
Gorleston	52°35′N	1°43′E
Margate	51°24′N	1°24′E
Netherlands		
Hollum (Amesland)	53°27′N	5°38′E
Den Helder	52°58′N	4°45′E
Naaldwijk	51°59′N	4°12′E
Germany		
Emden	53°22′N	7°13′E
Denmark		
Vestervig	56°46′N	8°20′E
Nordby (Fanø)	55°27′N	8°25′E
Norway		
Lista	58°06′N	6°34′E
Skudenes	59°09′N	5°16′E
Hellisøy Fyr	60°45′N	4°43′E

Total accession of fresh water to the North Sea. Table VI shows the total accession of fresh water to the North Sea, in cubic metres × 10^9, for each month from January 1941 to December 1960. These values are the respective sums of the values in Tables I and V.

TABLE VI—TOTAL ACCESSION OF FRESH WATER TO THE NORTH SEA

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						cubic metres × 10^9							
1941	49	66	63	44	45	46	69	90	35	77	60	67	711
42	55	31	46	41	57	49	78	59	76	99	61	78	730
43	78	63	37	56	59	68	55	71	62	62	78	41	730
44	74	46	40	47	53	70	62	56	85	77	102	85	797
45	61	84	46	52	72	67	56	62	56	58	38	68	720
46	53	82	57	49	47	74	85	78	92	40	82	62	801
47	41	27	80	63	46	60	51	16	60	38	80	51	613
48	109	62	39	49	48	65	61	73	82	76	54	66	784
49	74	46	45	57	55	53	48	52	51	84	69	78	712
50	47	73	49	52	51	71	79	84	97	69	83	72	827
51	76	62	63	66	49	52	63	91	61	34	95	80	792
52	74	47	63	52	53	61	64	78	77	66	79	81	795
53	51	56	37	50	58	62	75	80	58	51	67	56	701
54	52	44	45	31	54	69	76	74	86	106	87	95	819
55	70	54	43	41	59	54	50	39	63	80	40	77	670
56	88	37	42	34	49	66	82	90	57	82	54	73	754
57	67	77	64	34	43	56	81	84	88	80	66	65	805
58	74	76	55	44	70	62	91	88	59	79	51	71	820
59	82	26	44	55	37	51	52	44	23	59	76	72	621
60	70	53	33	39	44	49	63	76	59	90	93	89	758
Mean 1941–60	67	56	50	48	53	60	67	69	66	70	71	71	748

Acknowledgement. The author wishes to thank the various European hydrological and meteorological organizations which kindly supplied data and, in some cases, valuable comments on the data.

551.577.36(421)

AN INVESTIGATION INTO CONSECUTIVE WET WORKING DAYS AT LONDON WEATHER CENTRE

By H. V. FOORD

Summary. The number of consecutive wet days at London Weather Centre for summer and winter half-years from 1946 to 1971 was analysed to show the chances of completing an outdoor task requiring one dry working day if it were possible to allot one, two or three days to the project.

Introduction. Weather centres receive many requests regarding the possibility of performing a certain task on some days in the future, when the critical weather element is the absence of appreciable rainfall during the working day. Typical examples are: one-day building and decorating jobs, such as concreting, external paintwork or roof repairs; personal sporting activities, such as tennis or golf; outdoor social events, such as garden parties or presentations. Clearly the allocation of two or more days to the project (i.e. the task to be completed on the first day if dry; if not, then on the second day and so on) would result in a much higher probability of successful completion, but a quantitative assessment of probability has not hitherto been made.

Relevant information is not readily available, because most published rainfall data include periods outside the normal working day. An investigation was therefore made into the incidence of consecutive wet working days at London Weather Centre.

Procedure. The rainfall at London Weather Centre was analysed for the 25 years from April 1946 to March 1971 inclusive, yielding 25 summer half-years, from April to September inclusive, and 25 winter half-years, from October to the following March inclusive. The *Meteorological glossary* defines a wet day* as having one millimetre or more of rain in 24 hours, and wet working days for this investigation were classified as days when the rainfall between 09 and 18 GMT was one millimetre or more.

Frequency of consecutive wet working days. Table I shows the frequencies of single wet working days and sets of consecutive wet working days, as defined above, for each month and the total frequencies over the 25-year period. However, in order to decide the chances of achieving dry weather on one day by allotting a certain number of consecutive days to a

London, Meteorological Office. Meteorological glossary. London, HMSO, 1972, p. 314.*

project, sets with a high number of consecutive wet days must be taken to contribute to the sets of lower numbers of consecutive wet days, i.e. three consecutive wet days also count as three single wet days and as two occasions of two consecutive wet days, and so on. These cumulative frequencies are given in Table II for each month, together with the total frequencies for the 25-year period. The cumulative averages are given in Table III together with the annual averages and standard deviations and the monthly cumulative averages for the whole period.

Figure 1 shows the frequency distribution of the annual cumulative totals of single wet working days, whilst Figure 2 shows the frequency distribution for the annual cumulative totals of pairs of consecutive wet working days.

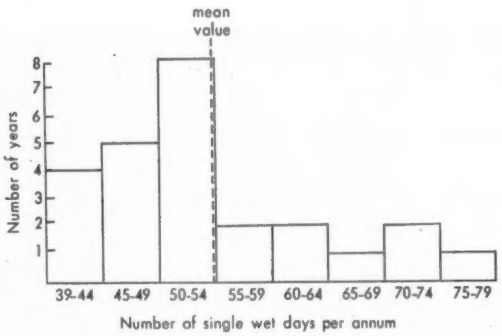

FIGURE 1—FREQUENCY DISTRIBUTION OF ANNUAL CUMULATIVE TOTALS OF SINGLE WET DAYS

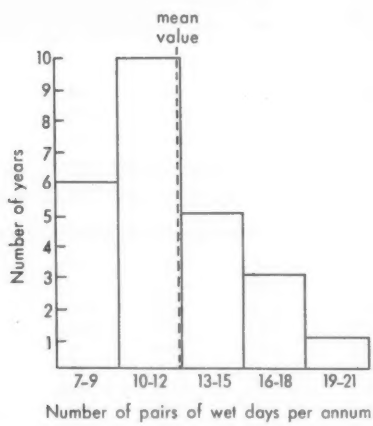

FIGURE 2—FREQUENCY DISTRIBUTION OF ANNUAL CUMULATIVE TOTALS OF PAIRS OF WET DAYS

Figures 1 and 2 both show that about 2/3 of the annual totals were at or below the mean annual value, with the wetter extremes in Figure 1 being thinly scattered. The distributions about the means are therefore not normal.

TABLE I—TOTALS OF CONSECUTIVE WET WORKING DAYS, APRIL 1946 TO MARCH 1971

	Consecutive wet working days					
	1	2	3	4	5	6
Jan.	67	14	4	0	0	0
Feb.	55	13	5	1	1	0
Mar.	58	13	2	1	0	0
Apr.	68	15	5	0	0	0
May	74	15	2	0	0	0
June	69	11	4	1	0	0
July	67	11	3	0	3	0
Aug.	73	18	4	2	0	0
Sept.	74	16	2	1	0	0
Oct.	75	12	5	0	0	0
Nov.	73	16	3	0	0	1
Dec.	75	17	2	1	0	0
Total for 25 years	828	171	41	7	4	1

TABLE II—CUMULATIVE TOTALS OF CONSECUTIVE WET WORKING DAYS, APRIL 1946 TO MARCH 1971

	Consecutive wet working days					
	1	2	3	4	5	6
Jan.	107	22	4	0	0	0
Feb.	105	30	10	3	1	0
Mar.	94	20	4	1	0	0
Apr.	113	25	5	0	0	0
May	110	19	2	0	0	0
June	107	22	6	1	0	0
July	113	29	12	6	3	0
Aug.	129	32	8	2	0	0
Sept.	116	23	4	1	0	0
Oct.	114	22	5	0	0	0
Nov.	120	27	7	3	2	1
Dec.	119	24	4	1	0	0
Total for 25 years	1347	295	71	18	6	1

TABLE III—CUMULATIVE AVERAGES OF CONSECUTIVE WET WORKING DAYS, APRIL 1946 TO MARCH 1971 INCLUSIVE

	Consecutive wet working days					
	1	2	3	4	5	6
Jan.	4·3	0·9	0·2	0	0	0
Feb.	4·2	1·2	0·4	0·1	0·04	0
Mar.	3·8	0·8	0·2	0·04	0	0
Apr.	4·5	1·0	0·2	0	0	0
May	4·4	0·8	0·1	0	0	0
June	4·3	0·9	0·2	0·04	0	0
July	4·5	1·2	0·5	0·2	0·1	0
Aug.	5·2	1·3	0·3	0·1	0	0
Sept.	4·6	0·9	0·2	0·04	0	0
Oct.	4·6	0·9	0·2	0	0	0
Nov.	4·8	1·1	0·3	0·1	0·1	0·04
Dec.	4·8	1·0	0·2	0·04	0	0
Annual mean	53·9	11·8	2·8	0·7	0·2	0·04
Annual standard deviation	8·1	3·4	2·0			
Monthly mean	4·5	1·0	0·2	0·06	0·02	0·003

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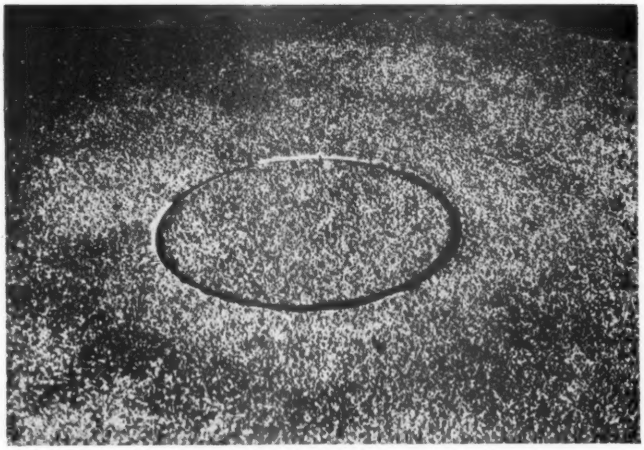

PLATE I—CLOSE-UP OF RAIN-GAUGE AREA SHOWING GRANITE CHIPS COVERING GAUGE AND SURROUND

See page 370.

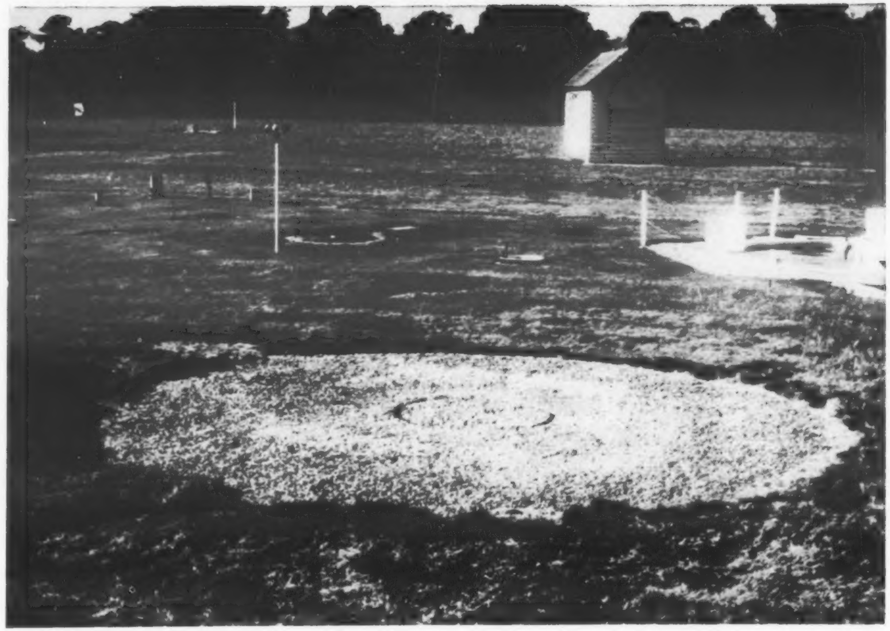

PLATE II—GENERAL VIEW TOWARDS THE SOUTH-WEST WITH RAIN-GAUGE AREA IN FOREGROUND

See page 370.

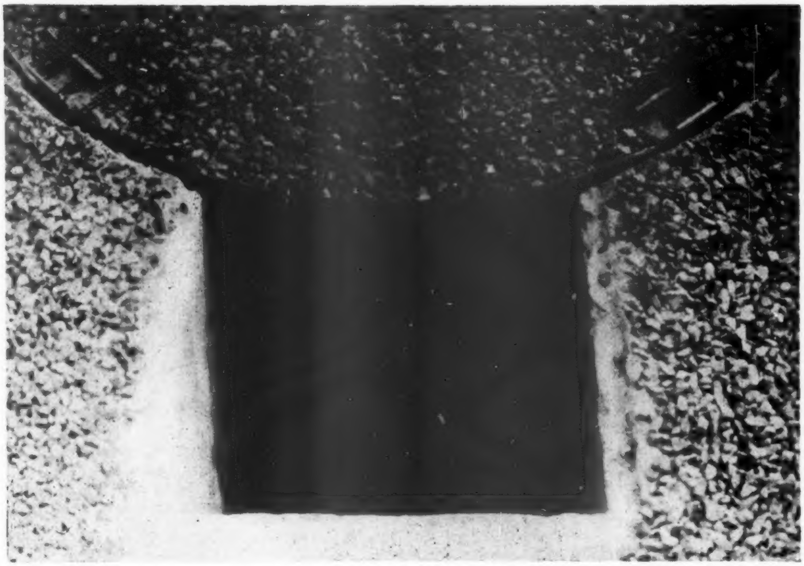

PLATE III—CLOSE-UP OF RAIN-GAUGE SHOWING STAINLESS-STEEL MESH
The access shaft is covered over when the rain-gauge is in use and is hardly visible, see Plate I,
See page 370.

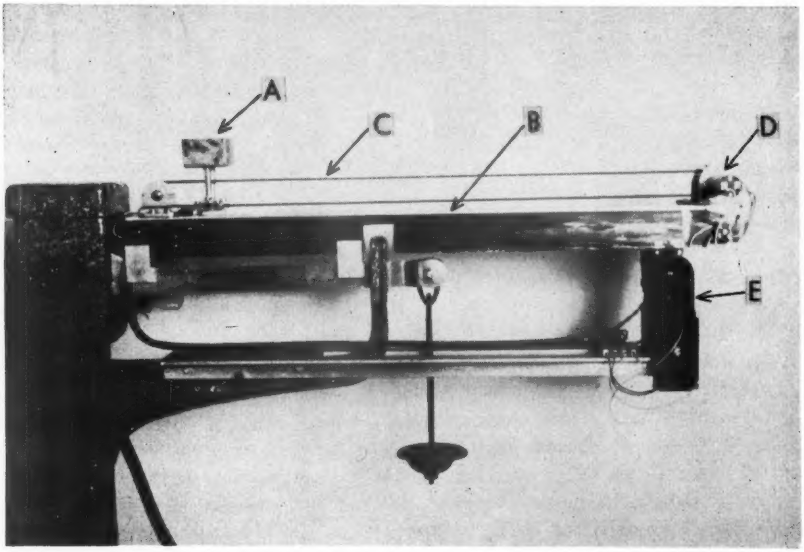

PLATE IV—WEIGHING-MACHINE USED IN GRAVIMETRIC RAIN-GAUGE
For identification of letters see page 370.

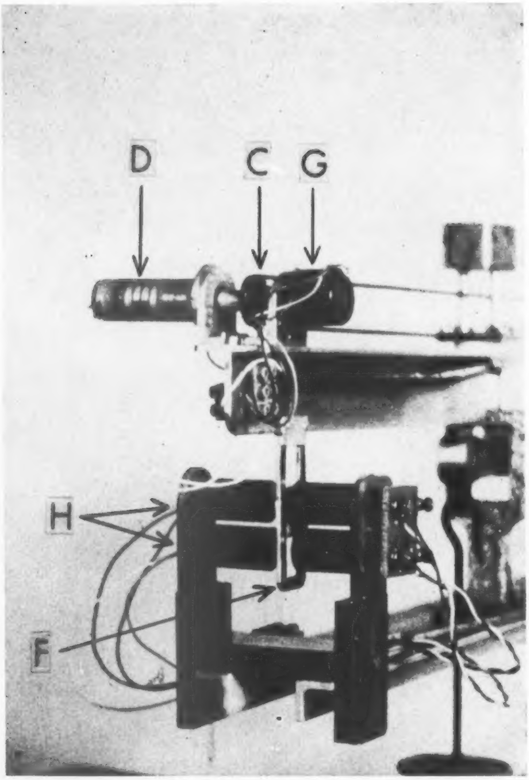

PLATE V—CLOSE-UP OF WEIGHING-MACHINE SHOWING AUTOMATIC BALANCING MECHANISM

For identification of letters see page 371.

Results.

Average annual data. In the period under review Table III shows that there were on average :

54 wet working days in each year (lowest total 39, highest total 78) with a standard deviation of 8·1,
12 pairs of wet working days in each year (lowest 7, highest 21) with a standard deviation of 3·4,
3 trios of wet working days in each year (lowest 0, highest 9) with a standard deviation of 2·0,
1 quartet of wet days approximately every other year,
1 quintet of wet days every 5 years,
1 sextet of wet days every 25 years.

Average monthly data. Similarly there were, on average, during the period under review :

between 4 and 5 wet working days in each month (lowest total 0, highest total 13),
1 pair of wet days in each month (lowest 0, highest 7),
1 trio of wet days in every 5 months (lowest 0, highest in one month 5),
1 quartet of wet days in every 16 months,
1 quintet of wet days in every 50 months,
1 sextet of wet days in every 300 months.

Probabilities. Using these past records therefore, anyone seeking to complete a one-day project in dry weather is :

85 per cent likely to complete if allotting only one day,
97 per cent likely to complete if allotting two consecutive days,
99 per cent likely to complete if allotting three consecutive days,

or, to put it another way, the likelihood of rain preventing completion is :

just under 6 to 1 against if only one day is allotted to a task;
30 to 1 against if two consecutive days are allotted;
122 to 1 against if three consecutive days are allotted.

Discussion. In 3 of the 25 years analysed there were no occurrences at all of three consecutive wet working days; in 15 of the years there were no occurrences of four consecutive wet days.

There were 13 individual months in the total period without any wet working days at all; these were quite evenly distributed through the year, one case occurring in each of February, March, July, August, September, October and December, and two cases in each of January, April and June. However, May and November always had at least one wet working day during this 25-year period.

The cumulative totals show that the monthly distribution is reasonably constant, but the number of wet spells rises to a peak in July, with August having a large number of pairs of wet days. February and November are the other months prone to consecutive wet days. However, one spell of six consecutive wet days in November tends to distort the cumulative figures for that month, which otherwise would have been very similar to October.

Whilst the variation in wet working days from month to month is small, the difference between summer and winter is remarkably small also. In fact the number of wet working days in the period October to March is slightly lower than in the period April to September. This could suggest convective influences giving rise to persistent showery situations in high summer.

During most of the period under review either British Summer Time or Double British Summer Time was in operation and thus for a part of most

years the normal working day started and finished earlier than the GMT hours used in the investigation. Perusal of the records revealed that quite often in the summer months the only rainfall was a heavy shower late in the day. The results shown here which refer to 09–18 GMT are therefore likely to be pessimistic compared with a working day of 09–18 BST, so the chances of dry weather in the summer half of the year should be greater than shown.

551.501.3

SI UNITS IN THE METEOROLOGICAL OFFICE

By F. E. LUMB

Summary. This article discusses the use of the International System of Units within the Meteorological Office.

Introduction. It is Government policy to introduce metric units in the United Kingdom by 1975,[1] based on the International System of Units (SI). A recent Government publication[2] indicates the state of progress towards metrication and the various agreements which will be required on entry to the European Economic Community. For the introduction of some units there may be a delay beyond 1975, but the maximum practicable progress towards the metric system is to be made within the next few years.

SI units. The British Standards Institution (BSI) and the Royal Society have for some time been encouraging users (schools, universities, industry) to adopt the SI, which uses the seven base units listed in Table I, in order to establish a familiarity with metre, kilogram, second units in practice before the eventual national change-over, and to avoid any unnecessary confusion with other forms of metric units such as are used in the c.g.s. system. The metre, kilogram, second units are large enough to satisfy general needs for practical measurements as well as for laboratory work and give a coherent system of derived units. Table II lists four important derived units with special names which are of fundamental importance in meteorology.

TABLE I—SI BASE UNITS

Quantity	Unit	
	Name	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

TABLE II—FOUR IMPORTANT SI DERIVED UNITS WITH SPECIAL NAMES

Quantity	Unit	
	Name	Symbol
Force	newton	N (see below for definition)
Energy, work, quantity of heat	joule	J (see below for definition)
Power	watt	W (1 W = 1 J/s)
Pressure	pascal	Pa (1 Pa = 1 N/m^2)

Definitions

newton: the force that produces an acceleration of 1 m/s^2 when applied to a mass of 1 kg.

joule: work done by a force of 1 newton in moving the point of application 1 metre in the direction of the force.

In addition, several units of great practical importance or useful in specialized fields of scientific research are to be retained. These include the degree Celsius; bar; degree, minute and second (of angle); and the minute, hour and day (of time).

Full details of SI units and of units outside the SI which are to be retained are given in a recent BSI publication.[3]

Between now and the national change-over the Meteorological Office wishes to co-operate in helping to publicize SI units, e.g. by encouraging the use of these units in Office publications. Wherever possible, texts will use SI units alone, but since meteorological work done in co-operation with other authorities may have to be presented in units commonly used in the United Kingdom by the authorities concerned, traditional units may be necessary for a time. If such units are used, SI equivalents or conversion factors will be given to help readers to gain familiarity with SI units before the complete changeover.

Some common meteorological units.

(a) *Millibar.* The millibar will be retained in name though its relation to the SI unit of pressure, the pascal (Pa), should be noted. Since the pascal is defined as the newton per square metre, it follows that the millibar is 100 pascals, or, in symbolic form, $1 \text{ mb} = 10^2 \text{ Pa}$.

In international journals the abbreviation mbar is being adopted because b is the symbol used for a unit (outside the SI) for effective cross-sectional area (the barn), but Meteorological Office publications are continuing to use the abbreviation mb since there is no possibility of confusion with the barn.

(b) *Temperature.* The base unit is the kelvin (abbreviation K), the degree symbol (°) having been dropped as unnecessary. The degree symbol is still required for Celsius temperatures (e.g. 5°C) but degC can be used to express a temperature difference (e.g. 5 degC).

(c) *Radiation flux.* The SI unit is the watt per square metre but the unit recommended by the World Meteorological Organization is the milliwatt per square centimetre, which is equivalent to 10 W/m^2.

(d) *Specific heat.* The joule replaces the various calories as the unit of heat so that in SI units specific heat is expressed in joules per kilogram per kelvin, or, in symbolic form, J/(kg K).

(e) *Distance.* For some time there will be a requirement for nautical miles and statute miles, and appropriate conversion factors will be quoted. Many conversion problems are easily solved by using duplicate scales on diagrams, e.g. feet and kilometres on cross-sections, each scale having its own natural steps of units.

Soil and earth temperatures are usually measured at depths of 5, 10, 20, 30 and 100 cm but some United Kingdom measurements are still made at 122 cm (4 ft). The bulbs of thermometers in the screen should be at 1·25 m above the ground but 4 ft (1·22 m) is acceptable for existing screens.

(f) *Speed.* The knot is the unit recommended by the World Meteorological Organization for horizontal wind speed for the time being, although a change to metres per second is envisaged for the future. The conversion $1 \text{ kt} \approx 0{\cdot}5 \text{ m/s}$ is sufficient for most practical purposes.

It is reasonable to use knots to give speeds of depressions, etc., especially when such speeds are to be compared with wind speeds in knots. If distances are measured in kilometres, the kilometre per hour (km/h) may be appropriate.

The abbreviation kt is at present used in Meteorological Office publications but kn is being used increasingly in international publications to avoid confusion with kilotonne (kt), the tonne (t) being 10^3 kg. Vertical speeds will be given in metres per second, except that for a time there may be some requirements in aviation (e.g. for gliders) and perhaps also in balloon calculations for the use of feet per minute.

(g) *Rainfall.* Depth of rainfall is now generally given in millimetres and it may be noted that 5 mm, for example, is equivalent to 5 kg/m^2 in SI units.

Series of data. A major problem arises with series of data over a long period of years including readings in different units. For example a series may contain 50 years of data in inches of rainfall and 5 years in millimetres, but with computer help there is little difficulty in using millimetres as the common unit. There may be other reasons for treating the series as two separate parts but results of calculations should be given in metric units. Similar problems arise with Fahrenheit and Celsius.

Acknowledgement. The author is indebted to Mr W. S. Garriock for much of the content of this paper, which is based on a report prepared by him for the Publications Committee of the Meteorological Office.

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551.508.77

A RECORDING GRAVIMETRIC RAIN-GAUGE — TOWARDS AN ABSOLUTE REFERENCE INSTRUMENT

By S. G. CRAWFORD

Introduction. Definitions of rainfall[1,2] usually state or imply that the ideal gauge should catch the precipitation which would have fallen on to an equivalent area of the ground had the instrument not been there. It has long been appreciated that the precipitation gauges commonly in use throughout the world fall short of this ideal mainly because of two principal sources of error.

If the receiving orifice is above ground level the instrument disturbs the natural airflow in a way which results in the deflexion of some of the raindrops, and a consequent loss of catch. Attempts to counteract this effect by the use of special shields appear not to have been successful.[3] Various modifications to the profile and internal shape of the gauge have been tried but inconsistencies in performance have not been eliminated.[4,5] Reynolds[6]

has pointed out that even if field trial comparisons of gauges did give reproducible data on their relative accuracy, information about their absolute accuracy would still be lacking, and it is this property which it is most important to establish. McCulloch[7] considers that the question 'How can point precipitation be measured to a known degree of accuracy?' is a fundamental problem of hydrology.

If the receiving orifice of the collector is brought down to ground level there is a risk that splashes from the nearby ground will carry additional water into the gauge. Various measures to subdue splashing or prevent splashes getting into the ground-level ('flush') gauge have been described by Bleasdale[8] who also proposed an ingenious anti-splash surround[9] which is in use at Kew Observatory in conjunction with an experimental comparison of evaporimeters. At Valdaj (the principal hydrological station of the U.S.S.R.) the upper surface of an extensive area of compact bushes, trimmed to a uniform height, surrounds a gauge having its orifice at the same level.[10] Because it is well known that a flush rain-gauge with 'anti-splash surround' collects more than a rain-gauge with its orifice above ground level, there has sometimes been a tendency to suppose that the flush-gauge catch is therefore 'correct'. It should be borne in mind that the various types of anti-splash surround, whether in the form of sloping slats resting on the ground or a grid accommodated in a shallow pit, constitute surfaces different from that of the surrounding terrain. It is possible, therefore, that they, too, may give rise to aerodynamically induced errors. Indeed, even if splashing is proved to be absent by an independent check such as the chemical tracer test used by Green,[11] the fact that the orifice of the collector is a 'hole' while the natural ground is 'solid' may raise doubts about the reliability of such rain-gauges, whether single or nine-hole.

The problem of eliminating disturbances caused by the instrument itself has been encountered in other investigations, notably the direct measurement of evaporation from a natural surface by weighing. Here, the use of the lysimeter is a well-established technique,[12] and it has been suggested[6] that a rain-gauge constructed to work on a similar principle would provide a 'standard' or 'absolute reference' against which other types of rain-gauge could be assessed. A description of such a rain-gauge, as realized at Kew Observatory, follows.

The collector and surround. In order to collect a representative sample of rain the container should be about a square metre in area and have its upper collecting surface identical and level with the surrounding ground. Any splashing should then cancel out across the perimeter. By using a circular collector the perimeter is kept to a minimum for a given area. A container of suitable size readily to hand was an American Class A evaporation pan, diameter nominally 120 cm. Its depth, 30 cm, is rather larger than necessary but not inconvenient. Careful measurements of the diameter indicated that 1 mm of rain over this area would weigh 1·146 kg.

It was anticipated that even if it were possible to simulate the grass-covered terrain of the experimental site there would be practical difficulties in ensuring that rain intercepted by such a surface would drain off rapidly enough into the collecting pan. Whipple[13] had shown experimentally that a surface of gravel was very effective in suppressing splashing. It was therefore decided

to use a similar surface composed of small granite chips. In order to minimize changes in aerodynamic roughness which might affect the airflow across the collecting pan, the grass on the immediately surrounding annular area 180 cm wide was removed by weed killer and the area was then completely covered with similar granite chips. Thus, apart from an essential gap a few millimetres wide between the pan and the surrounding 'guard ring', the receiving surface is virtually indistinguishable from the adjacent terrain (Plate I). The experimental site is flat, level and free of obstructions for 50 to 100 metres in all directions. Plate II shows a general view towards the south-west.

Four stout lugs are fixed just below the top of the inner wall of the pan for lifting purposes. About 2·5 cm below the top a strong stainless-steel mesh covering the whole area of the pan is supported on tightly stretched wires. The 18-gauge wire of the mesh is spaced at 8-mm intervals and provides adequate support for the granite chips which are typically 12 mm long (Plate III). The dry weight of the complete collector is about 82 kg. Although nothing is visible through the layer of granite chips, water can flow quite readily between them into the pan. The water which collects in the pan is removed by pumping out from time to time as part of the routine maintenance of the installation.

The weighing-machine and pit. The collecting pan is supported on an aluminium frame which is bolted to the platform of a bench-type weighing-machine of nominal capacity 100 kg. The whole assembly stands in a cylindrical concrete-lined pit, the height of the frame having been adjusted so that the top of the pan is level with the surrounding ground. The dry weight of the pan and frame is balanced by small weights added to the pendent tray.

Preliminary tests showed that the jockey weight on the balance arm ('steelyard') of the unmodified machine would give an indication of the load reproducible to within 60 g (this is equivalent to 0·05 mm of rain). This sensitivity was adequate for the present purpose. The working length of the original brass balance arm was 18 cm. In order to increase the capacity a longer piece of T-angle aluminium was bolted to it. Overall length was limited by the wall of the pit and after fitting other attachments the working length for the movement of the jockey weight was 38 cm (Plate IV).

The original jockey weight was removed and replaced by one of special design (Plate IV A) which slides along the upper flat surface of the aluminium arm (IV B). A small flat disc of polytetrafluoroethylene fixed to the underside of the jockey secures smooth motion without additional lubrication. The lower part of the jockey is clamped to a driving belt (IV C); the upper part is in the form of a small brass box. By putting the correct amount of lead into this box the overall weight of the jockey can be adjusted so that its maximum displacement along the arm corresponds to a convenient quantity of accumulated rainfall. At present the weight of the jockey is 354 g, equivalent to an accumulated rainfall of 50 mm. By decreasing the weight of the jockey, and accepting a reduced capacity, the sensitivity of the machine could be further increased to a limited extent, depending on the frictional resistance of the pivots.

The automatic balancing mechanism. The jockey is moved by an

endless non-slip driving belt which passes over toothed pulley wheels at either end of the beam (Plate V C). One of the wheels is driven by a small d.c. motor (IV and V D) working through a reduction gear-box. This wheel is fixed to the shaft of a high-resolution precision potentiometer (V G) which produces an electrical output proportional to the displacement of the jockey. The combined unit with supporting brackets weighs about 120 g. It is mounted at the outer end of the beam where its weight helps in backing-off the main load. The wires connected to the motor and potentiometer are brought along the side of the beam to a point as near as possible to the pivot end before passing to a terminal block fixed to the pillar of the machine. The polarity of the current to the motor is determined by two relays which are actuated by a simple optical switch (Plate IV E) so as always to be in a direction which causes the jockey to be driven towards the position of equilibrium. This results in a record which is slightly spread about its mean value as a result of the jockey hunting around the balance point (Figure 1). A micro-switch is interposed near each end of the beam so that if the jockey reaches an extreme position it switches off the current to the motor.

The optical switch. At the outer end of the beam, and fixed to its lower edge, is a small thin rectangular metal plate (Plate V F), the vertical movement of which alternately exposes the light directed towards two photo-sensitive cells (V H). The optical arrangement is such that the cut-off is very sharp and the 'dead-space', when neither relay is energized, is minimal. The extreme movement of the beam is limited by a pair of end stops (not shown in Plates IV and V) the separation of which has been reduced to the smallest value compatible with the exposed light being sufficient to operate the photo-cells.

All the electrical components at the weighing-machine are connected to their various supplies via a lead-covered multicore cable laid between the rain-gauge pit and a nearby underground chamber.

The light is from two 3·5-volt torch-bulbs which are under-run at 3·0 volts to prolong their life. They are supplied from a small mains transformer and rheostat. The light-sensitive units are photo-conductive cells whose large change of resistance with illumination triggers transistors controlling the relays. The latter are housed in a small box which also contains the other components required to operate the unit from mains supply.

The motor supply. The current for the motor is from a small mains transformer and rectifier. The voltage to the motor can be varied up to its full rating (28 V d.c.) to give a selection of speeds. For the main purpose of the gauge the tracking speed of the jockey is not important, but if rates of rainfall are to be inferred the speed must be sufficient to cope with the probable maximum. The highest rate of rainfall ever recorded at Kew over one minute is 300 mm/h.[14] The motor supply has been set at 10 V which gives a speed corresponding to about 400 mm/h.

The transducer. A millivolt analogue of the position of the jockey is provided by a precision 10-turn 5000-ohm potentiometer (Plate V G). To drive the jockey the full length of the beam requires $5\frac{1}{2}$ turns of the shaft. The resolution of the potentiometer, $1 \cdot 4$ in 10^4, is more than adequate for this purpose.

The potentiometer is supplied with about 30 mV highly-stable d.c. (better than 1 in 2000) from a mains-operated unit. The actual value is adjusted so that maximum traverse of the jockey produces full-scale deflexion on the recorder.

The recorder. The recorder is a multi-channel self-balancing potentiometer. In order to avoid errors due to possible slight misalignment between the printing type blocks, only one channel is connected to the transducer. It prints a small dot once per minute. Another channel is connected to a clock which produces a time mark every hour and a zero-reference record in between. An example of a rainfall record is shown in Figure 1.

The chart is usually driven at 1 inch per hour but can be run faster for special purposes, e.g. calibration. It has 100 divisions in a width of 25 cm. Using a vernier scale the record can be read to 0·05 division, so that with the 354-g jockey the difference between two readings might be subject to a maximum error equivalent to 0·05 mm of rain. A lighter jockey increases the resolution. The linear response of the recorder itself is separately checked from time to time.

Calibration. The weighing-machine is calibrated by simply adding weights to the collecting pan up to full-scale deflexion on the recorder and then removing them. The buoyancy error in substituting iron weights for the water to be collected (about 0·1 per cent) is negligible. To avoid pressure on the granite chips and their supporting grid, the weights are placed on a board set diametrically across the pan and resting on the rim. The chart is run at 50 mm per hour for clear separation of the dots. It has been found that 10 successive dots provide an average value reproducible to 0·01 division. The graph of displacement against load is linear. For the four calibrations made at intervals during the first two months of operational recording the slope of the line remained at 1·85 divisions per kilogramme, to within 0·1 per cent. This is equivalent to 0·480 mm rain per chart division, which is the factor used in scaling the rainfall record.

Evaporation. There is the question of evaporation from the collecting pan during the time rain is falling. Relative humidity during rainfall is generally below 100 per cent and may be as low as 80 per cent, even in a heavy shower. The gravimetric rain-gauge record shows the loss by evaporation quite clearly after the rain ceases (Figure 2). As would be expected the rate of evaporation during the time the granite chips are still wet is mainly affected by the meteorological conditions, with radiation predominating. The maximum rate observed so far (winter only) has been the equivalent of 0·07 mm/h. Once the stones are dry, a state which is very clearly revealed by their change of colour from almost black to light grey, evaporation from the water inside the pan is extremely slow and is probably mainly dependent on the stored heat. The records of evaporation under various conditions will provide a basis for estimating quite closely the loss during rain.

Any correction for evaporation during rain would usually be very small. There is some doubt, however, whether it should, in fact, be made at all. Rain falling on to the ground is also subject to evaporation, though the rate is likely to differ somewhat for different types of surfaces.

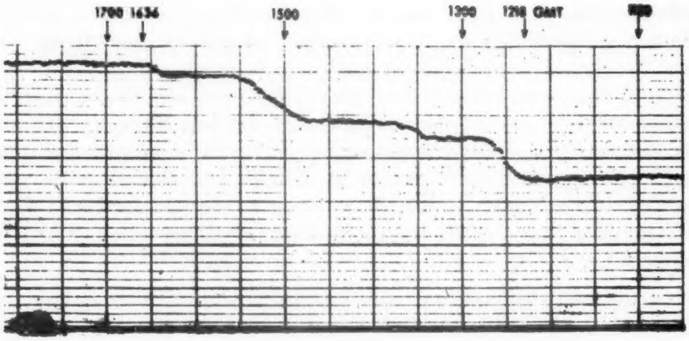

FIGURE 1—EXAMPLE OF A RAINFALL RECORD BY THE GRAVIMETRIC RAIN-GAUGE, 24 JANUARY 1972

The start of the trace shows evaporation after earlier rain. Continuous rain of varying intensity between 1218 and 1636 GMT gave a total of 6·41 mm. (1 large division = 2·4 mm.)

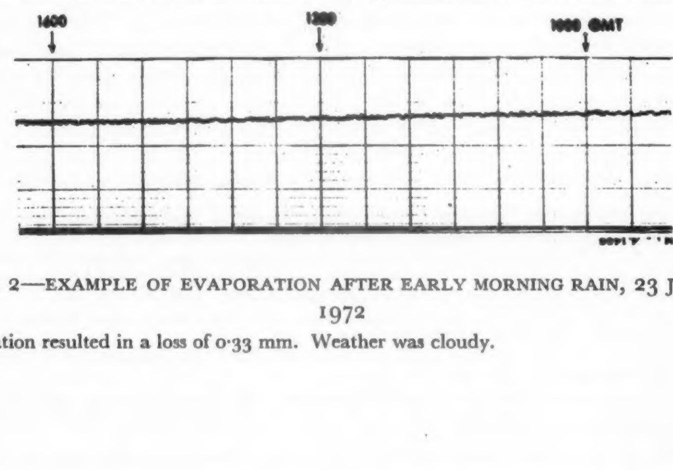

FIGURE 2—EXAMPLE OF EVAPORATION AFTER EARLY MORNING RAIN, 23 JANUARY 1972

Evaporation resulted in a loss of 0·33 mm. Weather was cloudy.

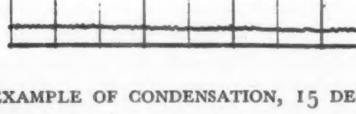

FIGURE 3—EXAMPLE OF CONDENSATION, 15 DECEMBER 1971

Condensation between 2000 and 2300 GMT resulted in 0·14 mm of dew.

Condensation. On clear nights when radiative cooling is pronounced, conditions are favourable for the deposition of dew or hoar-frost. On such occasions the deposit may be abundant on grass while meagre or even absent on bare soil, concrete, tarmac, etc. In the first two months of operation the gravimetric rain-gauge has clearly indicated the weight of the deposit on a number of occasions. In one case the equivalent of 0·14 mm was deposited in 3 h (Figure 3). When a period of rainfall is followed by a period of condensation it is necessary to refer to some other record in order to distinguish the two. At Kew the records from a radiation balance meter[15] or a rainfall chronograph[16] are used.

Experimental programme. The gravimetric rain-gauge is being used as a reference against which to assess the performance of other types of rain-gauge. At present these comprise two 5-inch Mk II gauges set at the standard height of 30 cm and one installed as a flush gauge with anti-splash surround.[9] The time of reading each of these rain-gauges is noted and the gravimetric rain-gauge chart is scaled over exactly the same interval. The limited results over the first two months of operation show, as might be expected, a relation between the gauges similar to that indicated in other work. It will, of course, be some time before sufficient comparison data covering a wide range of meteorological conditions are obtained.

Acknowledgements. The author is grateful to Mr R. H. Collingbourne, Mr D. R. Grant and Mr A. Bleasdale, all of the Meteorological Office, for very helpful discussions and suggestions. The electronics of the optical sensing device were due to Mr T. Stockhill of Action-Video Ltd. The construction and assembly of the modifications to the weighing-machine and collecting pan were skilfully engineered by Mr W. Wright in the Kew Observatory workshop.

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PLANS FOR TWO MAJOR METEOROLOGICAL RESEARCH EXPERIMENTS

Plans for two major meteorological research projects were discussed at two conferences held in Geneva in September 1972. These experiments fall within the Global Atmospheric Research Programme (GARP) which has been undertaken on a joint basis by the World Meteorological Organization (WMO) and the non-governmental body, the International Council of Scientific Unions (ICSU).

GARP Atlantic Tropical Experiment. The first experiment, known officially as the GARP Atlantic Tropical Experiment (GATE), which is scheduled for 1974, will involve the use of all modern meteorological observing techniques, including satellites, aircraft and ocean vessels. It will enable detailed scientific measurements to be made over about one-third of the world's tropical belt extending from the most western part of the Indian Ocean across Africa, the Atlantic Ocean, South and Central America to the most eastern part of the Pacific Ocean. Ships will be stationed over a large area of the Atlantic Ocean.

Particularly intensive measurements will be taken by radar-equipped oceanographic ships in a concentrated area of about 500 000 square kilometres centred at 25 degrees west and 10 degrees north in the eastern Atlantic. The present indications are that satellite observations will be obtained from American and U.S.S.R. satellites and that, in particular, a stationary satellite will be placed over the experiment area observing it 24 hours a day. About 12 to 15 specially equipped aircraft and about 25 scientific ocean research vessels will take part in the experiment, thus constituting what will probably be the biggest international fleet of ocean-going vessels ever assembled for peaceful purposes. While many of the highly developed countries of the world will be making substantial contributions to the experiment, its success will depend no less upon the active participation of the developing countries in the tropical regions of Africa and South America, and many countries from these regions, recognizing the scientific importance of the experiment, participated in the Conference. Senegal will have a particularly important role to play since Dakar will be the operational centre for the ships and aircraft taking part in the experiment.

An International Scientific Management Group (ISMG) will supervise the detailed arrangements for the planning and implementation of the experiment. The ISMG will conduct most of its activities at the headquarters of the Meteorological Office, U.K., where advanced computer facilities are available, and at the WMO secretariat in Geneva.

The main scientific aims of GATE will be to explore the primary energy source for the atmospheric circulations around the globe. This energy source lies in the tropical oceans which store the heat received from the sun. The mechanism by which this energy is transferred to the atmosphere is obscure, involving disturbances ranging from 10 to 10 000 km in size. These will be intensively observed by GATE, but once this mechanism is understood it is expected that advanced computer models will predict the daily weather not only in the tropics but at all latitudes for periods exceeding two weeks.

The First GARP Global Experiment (FGGE). This experiment, which is scheduled for 1977, will provide a global meteorological data set more complete than at any previous time in the history of meteorology. The scientific aims of the FGGE are to improve the knowledge and understanding of the global circulation of the atmosphere and of the physical basis of weather and climate and to develop more-realistic mathematical models for climate and extended-range forecasting.

The experiment, which will be of limited duration and based on recent technical and scientific advancements, will co-ordinate further work in these fields in all parts of the world.

WMO PRESS RELEASE

REVIEWS

Water balance of monsoon Asia, edited by M. Yoshino. 265 mm × 185 mm, pp. 308, *illus.*, University of Hawaii Press, Honolulu, 1971. Price: $16.

This beautifully printed and produced book is a collection of 15 papers by different authors, all of whom are Japanese. The studies concerned and the production of this book are connected with the International Hydrological Decade, and both were supported financially by the Japanese Ministry of Education. All parties involved are to be congratulated on a fine result, the usefulness of which is enhanced by good indexes both to the subject matter and to the authors cited — features which are far too rare in books compiled from the work of many authors.

The editor is professor of climatology in the Geography Department of the Hosei University, Tokyo, and has written a number of books, including a general climatology and another work devoted to small-scale climatology. He spent three years doing research at the University of Bonn and was later a visiting professor at the South Asian Institute of the University of Heidelberg. He is author or part author of three chapters in the book here under review.

The book is divided into five parts, all the parts and all the individual chapters being directed towards the water-balance theme but all interpreted in terms of a well-informed and up-to-date view of the role of the general atmospheric circulation, including such consideration of southern-hemisphere and complete Pacific patterns as is necessary. Much of the information given in the text and in the maps and diagrams will be new to readers outside Asia. Another unusually valuable feature is the well-balanced use of western (American, British, German, etc.), Russian, Chinese and Japanese sources listed in the 16 pages of bibliographies.

Very few faults were noticed. One, on page 7, is the unjustified assumption that all readers will know that Thornthwaite's 'famous PE index', which is mathematically defined, stands for precipitation effectiveness (not potential evaporation, as some readers of a chapter on 'Water balance problems . . .' are likely to expect). A few of the diagrams have inadequate captions; e.g. Figures 3 and 5 in the otherwise very good chapter on fluctuations of the rainfall in south-east Asia; in Figure 3 'moving average' appears to be a mistake for 'cumulative departure from average'; and in Figure 5 (a) the interesting plot of the rainfall in Peru, greatly varying from year to year in

relation to sea temperatures in the equatorial Pacific and the El Niño phenomenon, neglects to mention to which years the rainfall refers.

There are many interesting topics treated in the book, most of all, perhaps, the transport of water vapour over the monsoon regions of Asia which constitute the wettest region of its size in the world and are characterized by a great year-to-year variability in rainfall. This inevitably involves consideration of the proportionately even greater variability of rainfall in the equatorial Pacific (derived from air masses which also affect Asia) and the great anomalies of sea temperature there. However, the main sources of the water vapour are identified as the air-mass sources in the regions of the subtropical anticyclones over the oceans, though there is a contribution from evaporation over land in summer. The mean northward meridional transport of water vapour has its maximum near the 850-mb level at 35°N and exceeds the contribution of the eddy transport. There is also a net southward flux of water vapour from the Arctic Ocean over Asia in summer. There are fascinating maps of frontal frequencies and rainfall by 10-day periods over east Asia from May to July, maps of the position frequencies of the polar front and intertropical convergence and related wind flow in January and July, maps of mean wind velocity, sensible-heat supply, evaporation and Bowen's ratio over the west Pacific in January 1961 and profiles from 0° to 150°E of upper atmospheric pressure levels along the parallels of 30°N and 40°N, the July profile at 40°N being plotted together with the correlation coefficients between 500-mb height at each longitude and the month's rainfall at Bangkok, Hong Kong and Saigon.

Several chapters are concerned with secular change; one of these reviews, with maps and diagrams, the changes of the last 20 000 years over Asia from the maximum phase of the last glaciation through the post-glacial warmest millennia and derives some interesting points in terms of shifts of the general circulation pattern in the Asian sector which were new to this reviewer. The diagram on page 19 showing secular changes since 1885 of the spring rains in China suggested to the reviewer that the 90-year and 22–23-year oscillations might be playing a part in the story, the latter period being mentioned in the text as the strongest feature. The biennial oscillation (and other less-known periods) is said to be present in the annual rainfall record at Seoul, Korea, from 1770. A chapter, interestingly devoted to the regionality of secular variation of rainfall over monsoon Asia, reviews correlation studies between different places, and comes to the conclusion that there are many rainfall regions there with different secular variations. Only in winter some more widespread regions of coherent rainfall variation were found, and the variations were (not unexpectedly) correlated with the Siberian anticyclone and Pacific polar-front activity.

For so much information not readily available elsewhere and a handsome volume the price is not unreasonable.

H. H. LAMB

Introduction to the scientific study of atmospheric pollution, edited by B. M. McCormac. 240 × 165 mm, pp. v + 169, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht, Holland, 1971. Price: Dfl. 25 (paperback).

With the enormous increase of interest in pollution of the environment and the corresponding unprecedented growth in literature on the subject,

there is obviously a need for reliable and easily read summaries giving both a survey of the broad state of knowledge and a guide to further reading. This short book edited by B. M. McCormac, the editor of the recently inaugurated journal *Water, Air and Soil Pollution,* attempts this task for the multi-disciplinary aspects of air pollution.

There are chapters, contributed by several writers in U.S.A. and Canada, covering the types and sources of pollutants, meteorological aspects, effects on human health and vegetation, and the regular measurement of pollution.

The science and technology of all the various aspects have taken on such detail and complexity that substantial condensation and selection has been required to keep within the 150 or so pages. Judged by the section on meteorology this has been carried out with good judgement and a realistic assessment of the present state of the subject. Some omissions and obscurities are inevitable, but these are harmless provided the reader realizes, as the authors clearly intend, that further reference to detailed writings and latest experience will usually be necessary in any detailed practical application.

The non-meteorological aspects and the inevitable reflections on the philosophy of air-pollution abatement and control are presented objectively and without the sensationalism which is so easily engendered in the subject. Meteorologists will find these sections informative and a useful background to their own special professional interest.

The book is easy to read, and printing and illustrations are of good quality. In limp but serviceable covers the price is not unrealistic by current standards.

F. PASQUILL

Radar meteorology, edited by V. V. Kostarev, A. A. Chernikov and A. B. Shupyatskii. 245 × 175 mm, pp. v + 277, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £6·30.

This book contains a collection of papers presented at a conference in April 1968 (not 1965 as stated in the Preface). The conference was held at the Central Aerological Observatory whose Radar Meteorology Group is one of the largest of its kind in the world. The papers cover theoretical and experimental aspects and they demonstrate the wide application of radar techniques in the U.S.S.R. in the field of meteorology and hydrology.

The papers are concerned with the application of radar in the following main areas :

(a) the measurement of surface rainfall rate, hail size, and the microphysical properties of clouds;

(b) the measurement of winds and turbulence in the free atmosphere;

(c) absorption and scattering of radio waves in clouds,

(d) the nature and origin of radar echoes from the clear air;

and

(e) special radar equipment and data-processing techniques.

The papers vary greatly in standard; many, including some of the papers concerned with the quantitative measurement of rainfall rate, are marred by the use of 3-cm wavelength radars which suffer from problems of rainfall attenuation. Of particular interest, however, are papers dealing with the

measurement of hail size, and of rainfall intensity, using multi-wavelength techniques. Also of interest are reports of the successful use of polarization techniques for distinguishing between radar echoes from ice crystals and those from raindrops.

Papers concerning Doppler radar techniques are few in number; they mainly deal with the measurement of raindrop size distributions and the structure of turbulence in the planetary boundary layer. There are some interesting measurements of anisotrophy and energy dissipation rate.

The studies of clear-air echoes are disappointing; 3-cm radars of moderate sensitivity were used and many of the clear-air echoes were non-meteorological in origin and were probably due to insects.

There is a notable awareness of the practical value of radar for monitoring and forecasting local weather. An automatic device for the rapid digital processing of radar data is described which it is envisaged by the authors may form the basis for the creation of a unified national weather radar network.

K. A. BROWNING

Fundamentals of aeronomy, by R. C. Whitten and I. G. Poppoff. 233 × 180 mm, pp. xiv + 446, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1971. Price:£7.

This book on aeronomy — 'the science of the upper atmosphere' — is one of the latest in the *Space science text series* edited by A. J. Dessler and F. C. Michel in collaboration with a group of distinguished associate editors. The first two chapters contain historical material and brief reviews of some basic ideas in electrodynamics, thermodynamics, kinetic theory of gases, atomic and molecular structure and spectra, collision processes, and chemical reaction kinetics. Chapters 3, 4 and 5 deal, respectively, with problems in physical, chemical and fluid aeronomy, and the remaining chapters with various optical phenomena, electric currents in the upper atmosphere, the structure of the lower, middle, and upper ionosphere, disturbances in the ionosphere, and the propagation of electromagnetic waves in the ionosphere. A set of problems is presented at the end of each of the main chapters, where references are also given.

The book is evidently intended for use in a two-semester course at the senior undergraduate year or first-year graduate level, but with such a wide range of material to cover, the course would inevitably amount to nothing more than a general survey. Nevertheless, the book serves as a useful introduction to a variety of geophysical problems and to several branches of basic physics and chemistry, and as such provides a guide to more advanced work on the subject.

R. HIDE

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LETTER TO THE EDITOR

Coastal winds and cloud development

Mr Hindley,[1] in his description of a clear zone on the coast on 17 July 1971 has indicated that the cold coastal water is the reason for the lack of low-cloud development on the north-east coast (well shown on the satellite picture Plate I). On occasions such as this, when the flow is unstable north-north-westerly the lower surface temperature associated with the cold water anomaly, which is semi-permanent and caused by the strong tidal streams along this coast, is probably the main factor. However, on occasions when the sea-breeze is well developed, subsidence due to inland heating causing a sea-breeze circulation superimposed on the main stream often reduces maritime showers or disperses them altogether in the later morning and afternoon along the coasts. This is often very marked on the south coast of England and also in areas with onshore trade winds and monsoons.

Mr Rowles's[2] streamlines in his Figure 2, whilst naturally concentrating on the English side, would imply that the whole of the mid-Channel was a subsidence area, especially over the narrower portion, with streamlines flowing towards both coasts. This subsidence effect would also help to kill any convection over the middle of the Channel initiated by the slightly warmer water there.

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1. HINDLEY, D. R.; The importance of low sea surface temperatures in inhibiting convection along the North Sea coast in summer. *Met Mag, London*, **101**, 1972, pp. 155–156.
2. ROWLES, K.; Sea-breeze front near the south coast of England. *Met Mag, London*, **101**, 1972, pp. 153–154.

OFFICIAL PUBLICATION

The following publication has recently been issued :

Geophysical Memoirs

No. 116. British Isles weather types and a register of the daily sequence of circulation patterns, 1861–1971. By H. H. Lamb, M.A. (London, HMSO. Price: £3.)

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Other classifications made elsewhere in the world, especially those referring to the northern hemisphere, are also reviewed.


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